Student
Research Methods

The Search for the Hubble Constant

Abstract

The purpose of this inquiry is to find the Hubble constant or H_0. The Hubble constant is an approximation of the expansion rate of the universe. In order to find the Hubble constant, I calculated the redshift from the spectra of 9 galaxies and the angular diameter of these galaxies along their major axes. For these 9 galaxies, I calculated a value for the Hubble constant of 55.201 ± 8.691 km/s/Mpc (units = the speed of a galaxy 1 megaparsec away). This is fairly close to two recent Hubble Constant estimates of 73.8 ± 2.4 or 67.0 ± 3.2 km/sec/Mpc; measurements that differ because of the celestial objects used in the method of determination. However, the Hubble Diagram formed by the individual galaxy Hubble constants demonstrates the necessary linear relationship of Hubble's Law and the slope of the line formed is also a good estimate of Hubble's constant. If the value of the Hubble constant can be found, the curvature of space, the nature of dark energy, the true distances to distant galaxies and the age of the universe may no longer be unknowns.

Introduction

I was looking to do some sort of inquiry involving light and astronomy. At first, I originally wanted to find the distance to a supernova using its light curve and spectrum. Dr. Pawan Kumar gave me a link to a website with many light curves and spectra from Type I supernovae. However, finding the exact features of the spectra that matched to the elements in the supernova were very difficult to identify and hard to understand. But without this data, I would not be able to find the redshift, a key component in the formula.

I happened across a website in my search for an clearer explanation and found a site that shows how to compute the redshift of 15 galaxies, and the angular distances of those galaxies which are then used to calculate the Hubble constant. This was not only easier to do, but the Hubble constant is a fascinating value. It cannot only tell you the expansion rate of the universe but how long it has been expanding (since the Big Bang) and hence the age of the universe. This sounded exciting and also fit in with some of the research I had already been doing on my open-ended question on the acceleration of the universe. With 15 galaxies available to compute the Hubble constant, I was excited to finally be able to find the redshift and be on my way to finding the Hubble constant.

Background

For centuries, people have been studying the universe, looking for answers to life's many questions. Up until the 1920s, most scientists believed that the universe was composed of the Milky Way Galaxy. Edwin Hubble observed 18 Cepheid variable stars in spiral nebulae in 1922-1923 (Roos, 12). Cepheid variables are a class of variable luminous stars that can be anywhere from 4 to 20 times as bright as the sun. They are known as “standard candles” because they have fixed luminosities (Ryden, 114-5). The Cepheids in these “nebulae” that Hubble had been looking at proved to be too distant to exist in the Milky Way and were actual separate spiral galaxies outside of the Milky Way. This was the first definitive proof that showed the universe was not confined to the Milky Way Galaxy. He published a paper on his observations in 1925, which led the way for even more astounding ideas. His discovery in 1929 of a connection between the distances to nearby galaxies and the velocity of those galaxies led to the theory that the universe was expanding (Huchra, 2008). Hubble reasoned that if the velocity of distant galaxies was increasing with distance, the universe must be expanding so the galaxies had someplace to go (Narlikar, 31-2). This is considered one of the most important cosmological discoveries ever made and his findings fundamentally changed how scientists viewed this universe (Huchra, 2008). The relationship between the distance and velocity of nearby galaxies became known as Hubble’s Law.

This a picture of Edwin Hubble looking through the 100-inch Hooker telescope in the early 1920s.

http://hubble.nasa.gov/overview/hubble_bio.php

Hubble originally calculated a constant of about 500 (km/s)/Mpc. Trouble with this estimate began almost immediately in the astronomical community when

Hubble's calibration value showed that the Milky Way Galaxy was much larger than many of the nearby galaxies, despite the fact that the scale of the Milky Way was already known and established. Even though the constant did not prove to work all the time, astronomers continued to work with and use Hubble's value (Huchra, 2008). It eventually turned out that the stars in the most distant galaxies that Hubble had used in his measurements were actually star clusters, whose luminosity varies with distance. Therefore, Hubble's velocity/distance relation would not apply.

The value of Hubble's constant has been continually revised since it was discovered. However, many scientists could not agree on a value or even a range of values. The value was dropped to about 100(km/s)/Mpc by the 1960s but there was still not consensus. When the Hubble Space Telescope was launched, a project called the HST H_0 Key Project was started in order to find a more accurate value of the Hubble constant (within 10%) (Huchra, 2008). Observations of Cepheid variable stars, galaxy clusters and supernovae are still being used to try and pinpoint the exact value of the Hubble constant, particularly at long distances. It has been agreed that the value is between 50-100 km/s/Mpc but there are still major differences that exist in measurements released just a few months ago).

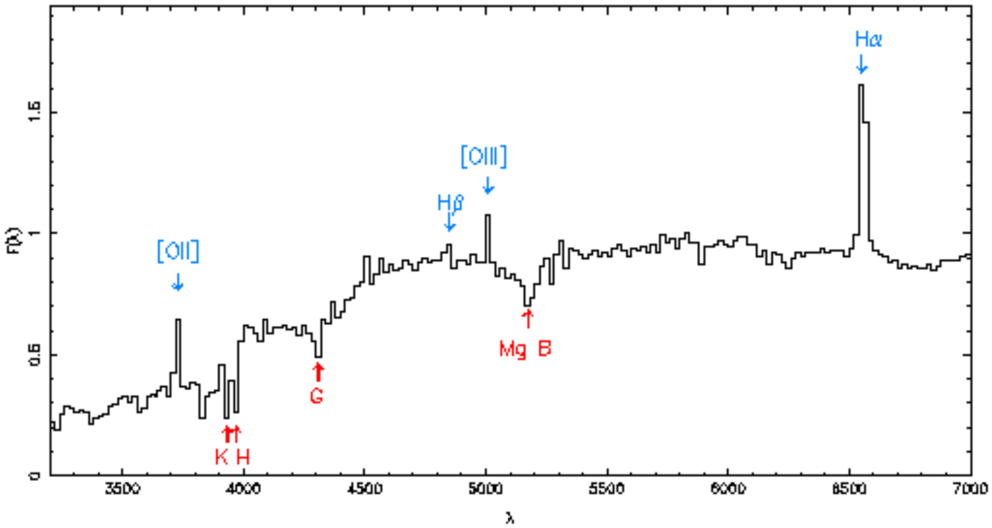
The Hubble constant is very important not only in measuring the distances to galaxies by knowing their velocities but also the age of the universe. It is also involved in calculations about the recently discovered accelerating expansion rate of the universe and dark energy as well as clearing the discrepancy between the expansion age of the universe and the age of the oldest stars found in globular star clusters.

The unit of measurements most commonly used today in association with the Hubble constant is (km/s)/Mpc. This comes from the velocity-distance relation that Hubble found in the 1920s. The km/s represents the velocity of the galaxy and the Mpc (megaparsecs) represent the distance to the galaxy. A megaparsec is about 3.3 million light-years.

Experimental Design

The data for this inquiry was found mostly on a website called "Measuring the Hubble Constant" written by Iain Smail. It is an experiment that contains the spectra and pictures of 15 galaxies. In this inquiry, I will be using 9 of these galaxies. Each galaxy has a light spectrum with four main emission lines marked as Hα, OII, OIII and Hβ. These lines are formed but the "recombination of ionized atoms in more tenuous gas in star-forming regions" (Smail, *Redshifts and Spectra*, 1998). An example spectrum is shown with the "restframe wavelengths" (given in Å = Angstroms).

Galaxy Spectrum (not redshifted)



(Smail, *Redshift and Spectra,* 1998).

These are the wavelengths of the four emission lines when the redshift z = 0. The observed spectra of 15 galaxies are then displayed so that the redshift can be measured. Redshift happens when light seen coming from an object increases in wavelength, or moves to the red end of the spectrum. The amount of shift is proportional to the increase of the galaxy's distance from Earth. The rate of that increase matches the rate of the expansion of space. Edward Harrison described it as the following:

"Light leaves a galaxy, which is stationary in its local region of space, and is eventually received by observers who are stationary in their own local region of space. Between the galaxy and the observer, light travels through vast regions of expanding space. As a result, all wavelengths of the light are stretched by the expansion of space" (315).

The formula used to measure the redshift is

$$(1 + z) = \lambda_{\text{observed}} / \lambda_{\text{emitted}}$$

where λ is the wavelength. The emitted wavelength is the value of the emission line in its "restframe" position and the observed wavelength is given in the spectrum of each galaxy. The values of the four emission lines we will be marking are the following:

Emission Lines	
[O II]	3727 Å
H-beta (Hβ)	4861 Å
[O III]	5007 Å
H-alpha (Hα)	6563 Å

(Smail, *Redshift and Spectra*, 1998)

The restframe spectrum shows examples of where these features can be found on the observed galaxy spectrum.

Solving for the redshift is only part of the equation for the Hubble Constant. The angular sizes of the galaxies had to be found by measuring the diameters along each galaxy's major axis. The distance of the angular diameter is defined as how near a celestial object is to us when the light we now see was emitted. This means that this measurement will be used to give us an angle of sight from here to the galaxy. This is not the "true" diameter of the galaxy.

On Smail's website, a picture was given taken from the Hubble Space Telescope. The picture is from an observation in 1995 of a small region of the sky called the Hubble Deep Field showing some of the faintest, most distant galaxies known. The website is equipped with a cursor that can choose one point on the galaxy and then can be dragged to another point. Once I dragged my cursor where I wanted it, a measurement in arcseconds would be displayed at the top of the picture.

Smail makes the argument that, "The last piece of information needed to estimate the Hubble constant from your observations is the mean diameter of a galaxy, D. D is estimated to be typically 20 kpc using the sizes of nearby giant Spiral galaxies for which accurate distances have been measured from Cepheid variable stars" (Smail, Calculation and Discussion of Results). The assumption made by the author is the galaxies are all approximately the same size.

An online lab from the University of Washington Astronomy Department explains that,

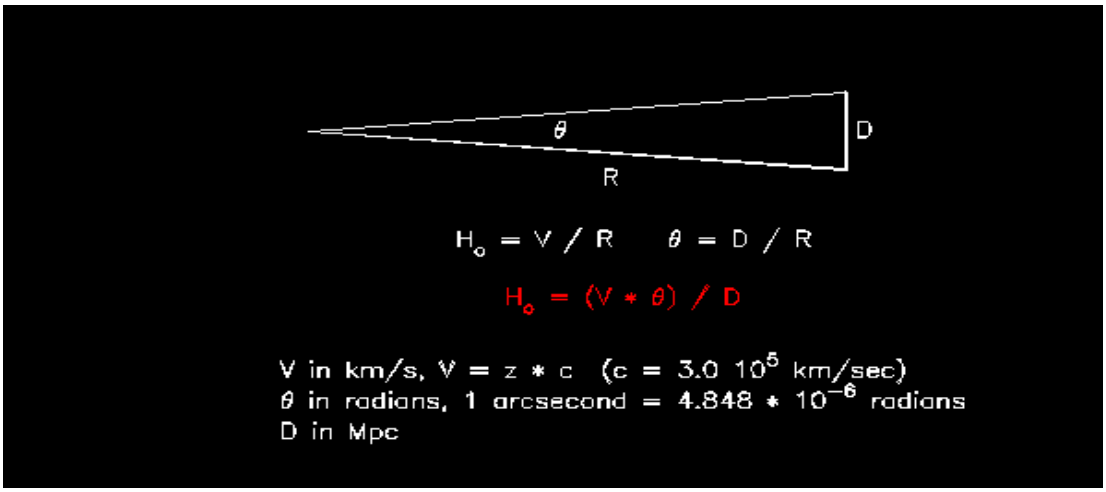
> "One may assume, for instance, that **all galaxies of the same type are the same physical size**, no matter where in the Universe they are. This is known as "the standard ruler" assumption. To use this assumption, however, we have to know the actual size of the "ruler" and to do that, we need the distances to the galaxies that form our standard ruler. So, since we are working with spiral galaxies, we choose nearby galaxies such as Andromeda, Triangulum, Messier 81, and others to which we have found an accurate distance measure using variable stars or other reliable distance indicator" (Mendoza and Margon, Step 3).

Smail used known distances of nearby spiral galaxies, like Andromeda, to Cepheid variable stars to find this particular mean galaxy diameter. Since the "standard ruler assumption" applies to the kinds of spiral galaxies that Smail referenced, the assumption of 20kpc can be justified.

At this point, we get the formula for the Hubble Constant,

$$H_0 = (V * \Theta) / D$$

where V is the recession velocity (how fast the galaxy is moving away from us), Θ is the angular diameter (angular diameter changed to an angle) and D is the mean diameter of the galaxy. Before we try to compute the Hubble constant, however, certain changes in units must be done first.



The recession velocity V must be in km/sec, Θ must be in radians and D must be in megaparsecs (Mpc).

As I explained above, Distance D is given as 20 kiloparsecs (kpc) as the estimation of the mean diameter for our galaxies. To change D to the correct units, we divide 20 kpc by 100 and get 0.02 Mpc.

For the angular diameters, we need to change from arcseconds to radians. We are given that

$$1 \text{ arcsecond} = 4.848 * 10^{-6} \text{ radians.}$$

Our last unit conversion is to find V. The recession velocity V is found by the following formula:

$$V = z * c$$

where c is the speed of light ($3.0 * 10^5$km/sec) and z is the redshift.

With these changes made we can now put them in the formula and find the individual Hubble constant for each galaxy. Finally, we average the individual

Hubble Constants that we calculated and to get an overall Hubble Constant for the 9 galaxies.

Analysis

Using the example of the given spectrum, we can find the redshifts of the 9 galaxies (displayed in Table 1 to 5 decimal points).

Table 1: Redshifts

Galaxy	G1	G2	G3 (N=3)	G4	G5 (N=3)	G6	G7	G8	G9
Hα	0.12987	0.14036	0.07874	0.31868	0.19936	0.13381	0.35277	0.21017	0.35539
OII	0.13535	0.14227	0.07993	0.23463	0.19999	0.13766	0.35469	0.28081	0.35931
OIII	0.13040	0.14415	0.08228	0.31085	0.20258	0.13727	0.35554	0.28164	0.35897
Hβ	0.12894	0.13956		0.25109		0.13248	0.35199	0.27233	0.33252
Mean Redshift ($\bar{z}$)	0.13114	0.14159	0.08032	0.27881	0.20065	0.13530	0.35375	0.27624	0.35155

For those galaxies where I could only find 3 of the four emission lines, I have denoted it by putting (N = 3).

I measured the angular diameter of each galaxy with the cursor 3 times. These are the measurements I received.

Table 2: Angular Diameters (arcsec)

Galaxy	G1	G2	G3	G4	G5	G6	G7	G8	G9
Angular Diameter (d) - arcsec	4.9336	4.56070	2.69258	8.27587	2.94188	5.69386	2.81780	2.90689	3.04631
	4.0719	4.83011	2.58070	8.06040	2.95466	5.23546	2.90689	2.76586	3.08707
	4.3290	4.60435	2.78927	8.62786	3.18277	5.88982	2.96816	2.92746	2.88617
Mean Diameter	4.44480	4.66505	2.68752	8.32138	3.02617	5.60638	2.89762	2.86674	3.00652

In order to calculate Hubble's constant, we need to get the values of the mean diameter D, the recession velocity V and the angular diameter distance Θ in their correct units. From the website, we are given the Distance D = 20 kiloparsecs (kpc). This measurement was found from the estimation of the distance from several spiral galaxies to Cepheid variable stars. Given a table of the Cepheid distances of 17 spiral galaxies, we can use the measurements of their true diameters in order to calculate the error for the given measurement of 20 kpc. Though the galaxies are not the same ones used in this particular inquiry, the standard error found from these 17 spiral galaxies is a good approximation for the standard error for the 9 galaxies specified here. The exact error is therefore calculated as

$$\Delta D = 0.919 \text{ kpc.}$$

To change D into the correct units of Megaparsecs, we divide 20 kpc by 100 and get

$$D = 0.02 \text{ Mpc} \pm 0.00919 \text{ Mpc.}$$

For the angular diameters, we need to change from arcseconds to radians. We are given that

$$1 \text{ arcsecond} = 4.848 * 10^{-6} \text{ radians.}$$

We therefore multiply our values for the angular diameters by $4.848 * 10^{-6}$ and get the values we need for Θ (to three decimal places in Table 3). The "E-05" means "multiplied by 10^{-05}".

Table 3: Angular Diameters in radians

Galaxy	G1	G2	G3	G4	G5	G6	G7	G8	G9
Angular Diameters Θ (radians)	2.155 E-05	2.261 E-05	1.303 E-05	4.034 E-05	1.467 E-05	2.718 E-05	1.405 E-05	1.390 E-05	1.458 E-05
Standard Error (Δθ)	1.238 E-06	4.047 E-06	2.921 E-07	8.018 E-07	3.800 E-07	9.400 E-07	2.116 E-07	2.462 E-07	2.972 E-07

Our last unit conversion is to find V. The recession velocity V is found by the following formula:

$$V = z * c$$

where c is the speed of light ($3.0 * 10^5$ km/sec) and z is the redshift. When we finish the calculations, we get these values (to one decimal place).

Table 4: Recession Velocity

Galaxy	G1	G2	G3	G4	G5	G6	G7	G8	G9
V = z * c (km/sec)	39340.5	42476.0	83643.9	24094.7	60193.9	40591.3	106124.4	82870.7	105464.8
Standard error (ΔV)	430.277	307.538	6326.553	311.731	571.390	383.413	246.773	875.136	1921.221

We can finally put all of the values together to get the following Hubble constants, one for each galaxy (to five decimal places. The formula is

$$H_0 = (V * \theta) / D$$

Table 5 lists the value of the individual Hubble constants.

Table 5: Hubble constants

Galaxy	G1	G2	G3	G4	G5	G6	G7	G8	G9
Hubble Constants (H_0)	42.38781	48.03225	54.49014	48.60139	39.14780	55.16302	74.53995	57.58660	76.860
Standard Error (ΔH_0)	19.63502	22.09103	25.40539	22.35887	18.02246	25.42530	34.27110	26.48857	35.381

Once we have found the individual Hubble constants, we can now find the mean Hubble constant H_0 for all 9 galaxies.

$$H_0 = 55.20106$$

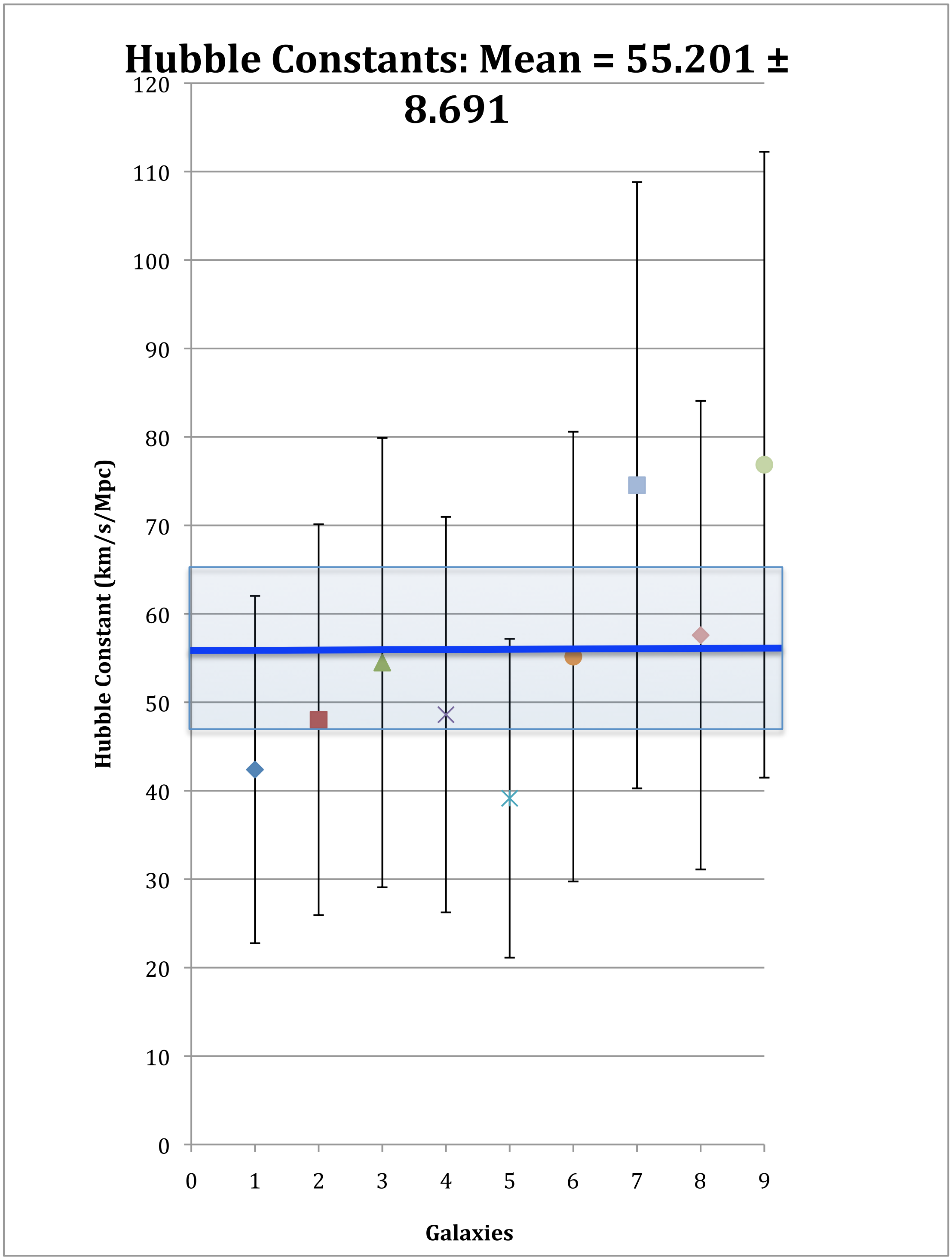
with a standard error of

$$\Delta H_0 = 8.69094$$

The following is the graph (Graph 1) of the individual Hubble constants for these 9 galaxies. The blue line represents the mean of 55.20106 and the shaded area is the standard error around the mean.

As you can clearly see, the error bars for all the individual Hubble constants all overlap, showing that there is not a significant difference between these values. Also, the mean crosses each of the error bars of the individual Hubble constants and shows that the mean is not significantly different from the individual Hubble constants.

Graph 1



We need to check and see if the differences between the mean H_0 and the individual Hubble constants are "statistically" significant. To do this, we must perform a χ^2 test. In order to perform a χ^2 test, a null hypothesis is needed. To test if the values are different, we get the following null hypothesis:

> **Null Hypothesis**: There is no difference between the Hubble constants of the 9 galaxies and the mean of 55.20106.

The result of the χ^2-test will be in the form of an interval for the "p-value". The p-value is the probability that the difference between the means of the Hubble Constants is due to chance. If the p-value falls outside the standard value of 0.05 (represented by α), then the null hypothesis cannot be rejected and we must accept that the difference between the mean of the Hubble constant and the individual Hubble constants is due mostly to chance and is not "statistically significant". Otherwise, we reject the null hypothesis and the difference between the means is statistically significant and the difference is due to chance less than 5% of the time. The formula for the χ^2 test is as follows:

$$\chi^2 = \Sigma\ [(x_i - \mu) / \Delta x_i)^2]$$

where μ represents the mean of the Hubble constants (55.20106) and x_i represents the individual Hubble constants that were listed in Table 5 above.

When we run the χ^2 test we get:

$$\chi^2 = (-\ 0.652571372)^2 + (-\ 0.324512316)^2 + (-\ 0.027983069)^2 + (-\ 0.295170096)^2 + (-\ 0.890736607)^2 + (-\ 0.001496206)^2 + (0.564291361)^2 + (0.090059132)^2 + (0.612177919)^2$$

$$\chi^2 = 2.113777209$$

The degrees of freedom are the number of independent terms, in this case, df = 8. By looking at the table, we find our p-value:

$$\text{p-value} > 0.25$$

Since our p-value > α = 0.05, we do not reject the null hypothesis. Therefore, our statistics test shows us that the differences between the mean H_0 and the individual Hubble constant are not statistically significant.

Using our value of H_0 and the Hubble constants from Table 5, we can find the following confidence interval:

A 95% confidence level test shows that the value of the true mean of the Hubble constant falls between 46.51011 and 63.89200 km/sec/Mpc.

The consensus exists that the true value of the Hubble constant is within the interval of 50 -100 km/sec/Mpc, though the exact number still eludes scientists. Researchers and astronomers, along with the Hubble Space Telescope, continue to work on narrowing the range of values though different teams still get vastly different numbers. A report in 2001 from two teams working on the HST (Hubble Space Telescope) Distance Key Project calculated two very different values for the Hubble constant. One team received a value of 72 ± 8 km/sec/Mpc. Another team, working with almost the same data, calculated a value for the Hubble constant of 57 ± 4 km/sec/Mpc. The average of this data is 65 ± 8 km/sec/Mpc, and, at the time, was consistent with some other results by two other teams who were using the Hubble constant to find the age of the universe.

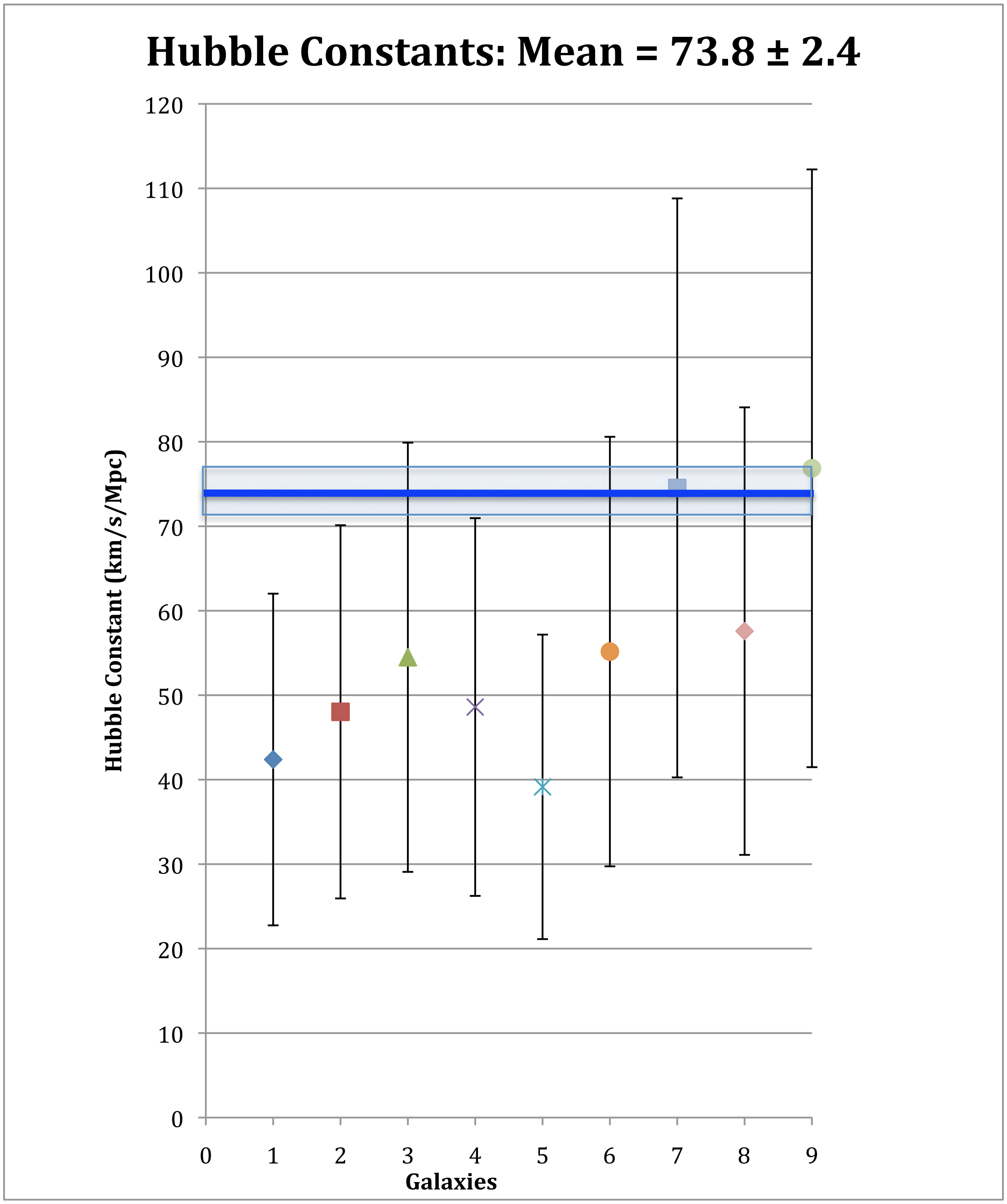
In 2011, a new estimate for the Hubble constant was calculated, using data from Type Ia Supernovae. Adam Reiss published the new value of

$$H_0 = 73.8 \pm 2.4 \text{ km/sec/Mpc}$$

in April 2011 (Reiss, 1).

On Graph 2, the blue line marks the Hubble constant value that Riess calculated. The shaded area displays the standard error.

Graph 2



This line representing the value 73.8 does not intersect with all the lines of error of the individual Hubble constants. However, it does clearly intersect 5 of them (galaxies 3, 6, 7, 8 and 9) and is very close to a sixth (galaxy 4). To find out if there is any significant difference between this mean and the Hubble constant values of the individual galaxies, let us perform another χ^2 test. This time $\mu = 73.8$.

Our null hypothesis is very similar to the null hypothesis in our first test, except the value of μ has changed.

> **Null hypothesis:** The individual Hubble constant values are the same as the value 73.8.

Once again, the formula is

$$\chi^2 = \Sigma\left[\left((x_i - \mu) / \Delta x_i\right)^2\right]$$

So,

$$\chi^2 = (-1.599804135)^2 + (-1.166434865)^2 + (-0.760069314)^2 + (-0.863633178)^2 + (-1.92272334)^2 + (-0.733009366)^2 + (0.021591045)^2 + (-0.612090358)^2 + (0.086503729)^2$$

$$\chi^2 = 9.86028264$$

In this problem, we have 9 independent terms so df = 9. Looking at the table, we find

$$\text{p-value} > 0.25$$

Since the p-value > $\alpha = 0.05$, we do not reject the null hypothesis. This shows that there is no statistically significant difference between the Hubble constants of the 9 galaxies and the value that Adam Riess calculated this year.

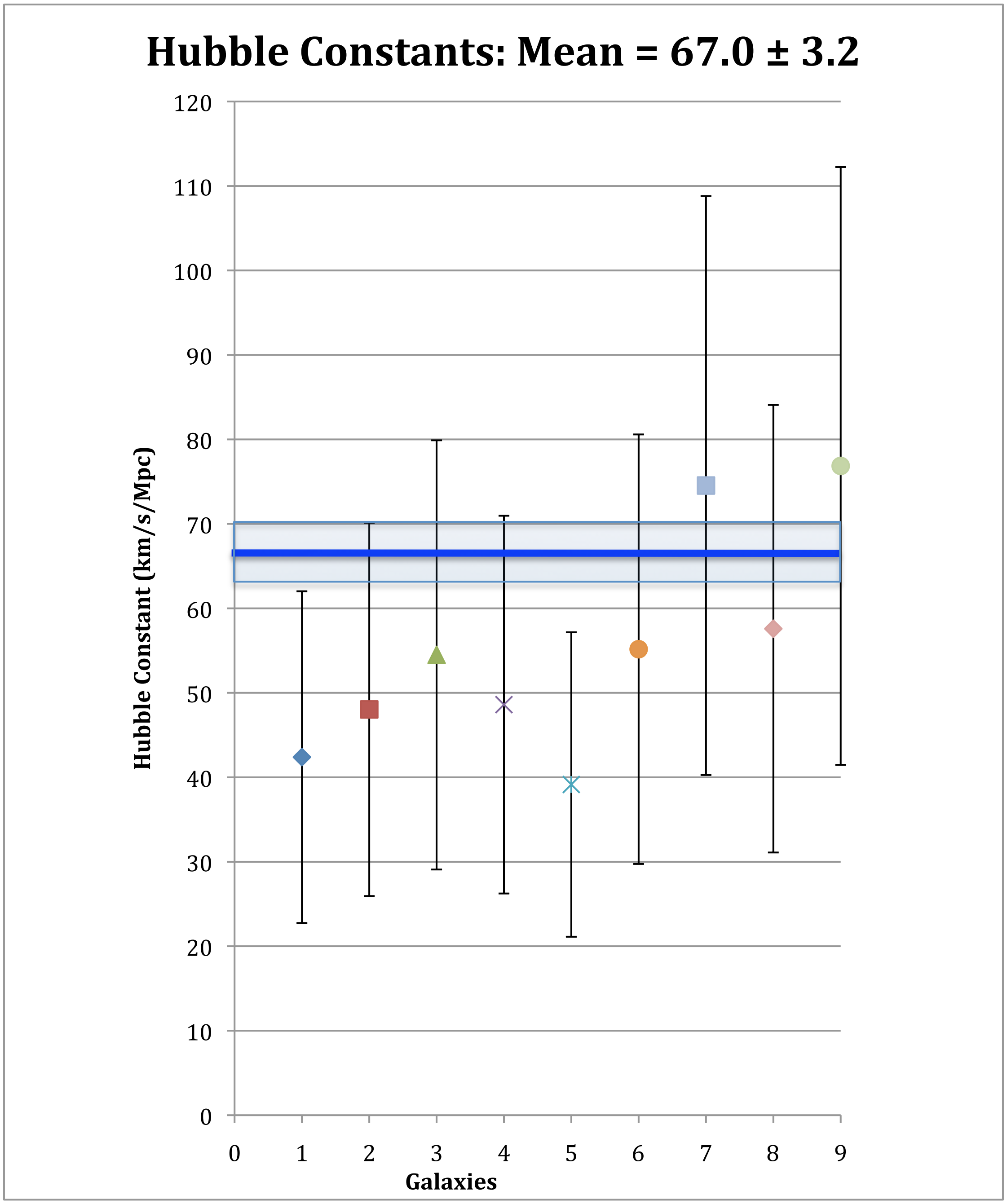
Using Riess's value of H_0 and the Hubble constants from Table 5, we can find the following confidence interval:

> A 95% confidence level test shows that the value of the true mean of the Hubble constant falls between 71.4 and 76.2 km/sec/Mpc.

By calculating the error intervals of the five galaxies that intersected the line of 73.8, we can see that they all have values that fall in this range. Galaxy 4 only misses this interval by 0.5. However, we also notice that the mean received by our calculations is not within this interval and the highest number in its confidence interval (63.892 km/sec/Mpc) is also not within the 95% confidence interval of Riess's new approximation for H_0.

In October of 2011, another paper was published offering a different estimate of the Hubble constant. Another team of scientists working with galaxy clusters and the Wilkinson Microwave Anisotropy Probe-7 (WMAP-7) had found a Hubble Constant of 67.0 ± 3.2 km/sec/Mpc (Beutler et al., 2011). Graph 3 shows the same values of the individual Constants that I calculated in Table 5.

Graph 3



The dark blue line is 67.0 with the shaded area encompassing the interval within its standard error. This line seems to fit my data better than Riess's value for H_0. The blue line intersects the error bars of 7 of the galaxies and is very close to galaxy 1.

Once again, it would a good idea to do another χ^2 test to see if there is a statistically significant difference between the individual Hubble constants and the value found by Beutler's group. The null hypothesis is very similar.

Null hypothesis: The individual Hubble constant values are the same as the value 67.0.

First we calculate

$$\chi^2 = (-1.253484222)^2 + (-3.032904835)^2 + (-0.492409606)^2 + (-0.559503279)^2 + (-1.545416336)^2 + (-0.465559185)^2 + (0.220008935)^2 + (-0.355375895)^2 + (0.278696658)^2$$

Then,

$$\chi^2 = 14.18267036$$

Like the previous test, there are 9 independent terms so there are 9 degrees of freedom. Looking at the table reveals

$$0.10 < \text{p-value} < 0.15$$

While the value of χ^2 is bigger than the value in the other two tests, it still gives a p-value that is greater than $\alpha = 0.05$. The null hypothesis is also rejected and the difference between this other new number of 2011 and the individual Hubble constants is not statistically significant.

Both of these numbers are extremely recent findings but it is interesting to note that neither is within the error intervals of the other. It is obvious when looking at the 95% confidence intervals.

We know from the first value that the 95% confidence interval is from 71.4 to 76.2 km/sec/Mpc. For the value of 67.0, the 95% confidence interval is between 63.8 and 70.2 km/sec/Mpc. That leaves a minimum distance of 1.2 between the two values for H_0. That may not seem like a lot, but these scientists have measured so many galaxies and supernovae that such a large difference is surprising.

It is interesting that the value for the mean of the individual values just overlaps the interval given by the value of 67. The highest possible value for the mean is 63.892, which is just within the lowest possible value of 63.8. It is fascinating that only working with 9 galaxies that had high rates of error still gave me a number that fits a value that some of the smartest astronomers of the world are coming up with. I was within the range of 50-100 km/sec/Mpc!

<u>Error</u>

This difference between the H_o received by our calculations and the H_0 received by Riess means that there was a lot of error in my calculations. I was only dealing with 9 galaxies, while Riess was handling measurements from dozens of supernovae. Also, I am unfamiliar in finding redshifts and many of my values have huge errors. The error for the true diameter of the galaxies was calculated from a set of galaxy measurements that do not correspond to the galaxies that I used in this inquiry. Also, the measurements of the major axis for the angular diameter may be off since I was just dragging my cursor along what appeared to be the major axis. I tired to limit the error for angular diameters by taking 3 readings instead of 1. These are just a few of the possible errors in the reading and calculations that might have occurred. However, the error does not seem so great since I was able to overlap with Beutler's findings (even if by a small margin).

Hubble Diagram

Figure 1 is a picture of the Hubble Diagram that Edwin Hubble first drew in 1929.

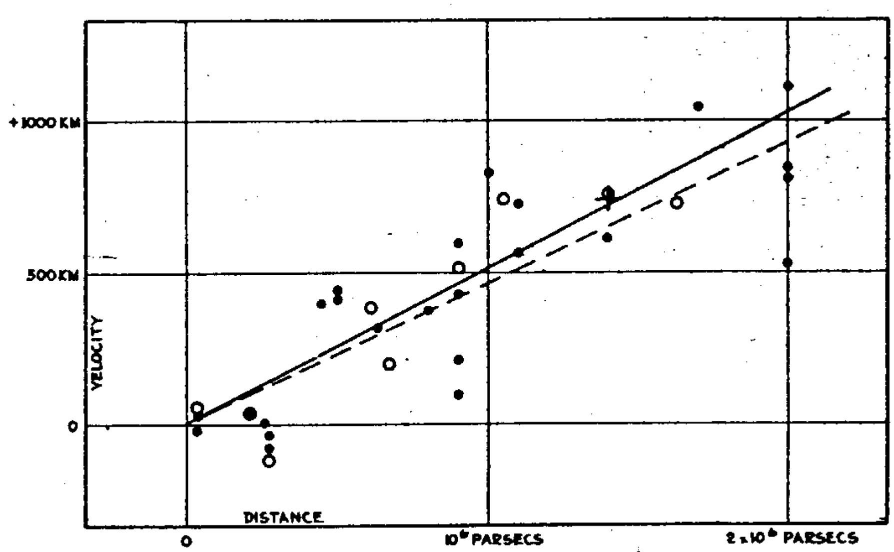
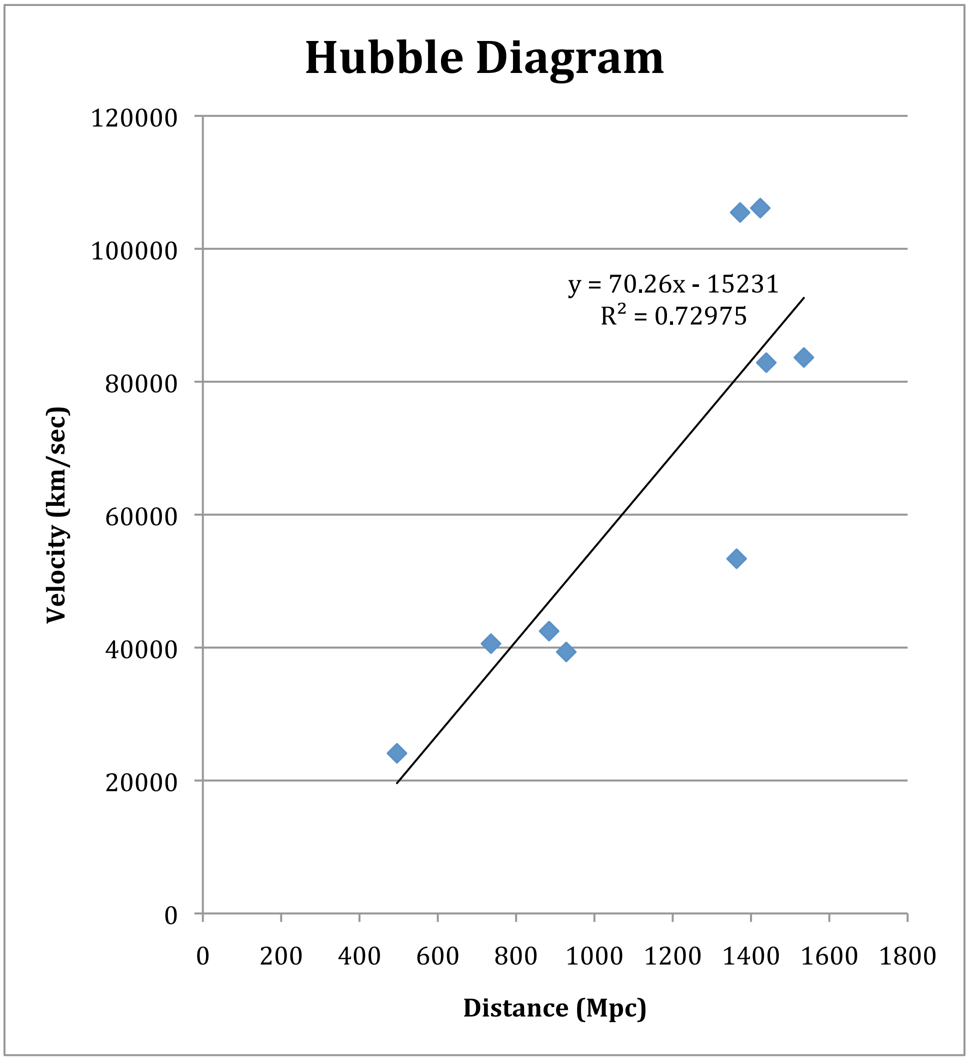


FIGURE 1

Hubble, PNAS 15, 168 (1929)

The y-axis is the recession velocity and the x-axis is the distance from us to the object measured. The slope of the fitted line in Hubble's diagram was 464 km/sec/Mpc. and was one of his first approximations for the Hubble constant (Wright, Part 1).

Whatever the actual value of the Hubble constant, the value I received from the 9 galaxies I chose from the website did provide me with enough data for my own Hubble Diagram. The slope I got from the fitted line is 70.26 and a good approximation for the Hubble constant. It is much closer to Riess's value than the mean of the individual Hubble constants and even closer to the value found by Beutler (it is within the confidence interval).



The linear relationship that appears in the Hubble Diagram is a consequence of Hubble's Law. This Law was can be stated mathematically as

$$V = H_0 * D$$

where V is the recession velocity, H_0 is the Hubble constant and D is the distance between the Milky Way Galaxy and the distant celestial object. This equation shows that the redshift, and thus the recessional velocity, is proportional to its distance from our galaxy. In other words, the velocity of distant galaxies increases (linearly) as its distance away from us increases. This explains the direct proportion in the equations and linear form in the graph.

With the many new discoveries about the expansion of the universe, the "constant" part of Hubble's is no longer particularly true, but even when the scale of the axes of the Hubble Diagram has to increase exponentially (to account for acceleration), the linear form of the fitted line still holds (Narlikar, 31-32).

Conclusions

Knowing the exact value of the Hubble Constant would be an amazing step and lead to so many other discoveries. One of these would be the exact age of the universe, another number that is still trying to be discovered. The most recent estimate to about 1% is 13.7 ± 0.13 billion years (Wollack, 2010). The usefulness of the Hubble Constant comes from the formula that scientists use to calculate this age. They can extrapolate the age of the universe by using $2/(3\ H_o)$ if the universe has a high mass density or by $1/\ H_o$ if there is a low density of matter (Wollack, 2010).

With the discovery of an accelerating universe, dark energy and the nature of dark energy have become an increasingly important area of research. Scientists are using Hubble's value to see, "how the Hubble constant affects the constraints on dark energy and/or the curvature of the universe" (Ichikawa and Takahashi, 2008). Using the Hubble Constant to test and constrain the nature of dark energy is effective because of the effect that dark energy has on the expansion rate of the universe (H_0). Investigations into alternative explanations, other than the cosmological constant of Einstein's, are important in further narrowing the parameters and characteristics of dark energy. Ichikawa and Takahashi are two physicists that are no longer content with, "simple dark energy models such as a cosmological constant and a constant equation of state [that] are usually assumed" (2008). In a recent publication, they have stated their purpose as the following:

> "Since we do not know the nature of dark energy yet, it is interesting to investigate the Hubble constant assuming some types of dark energy and see to what extent the constraint on the Hubble constant is affected by the assumption concerning dark energy" (2008).

This seems to be one of many fascinating ways to use the Hubble Constant as researchers around the world try to find the elusive value that Hubble experimented with decades ago.

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